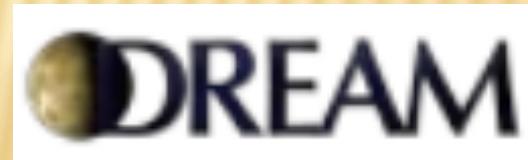


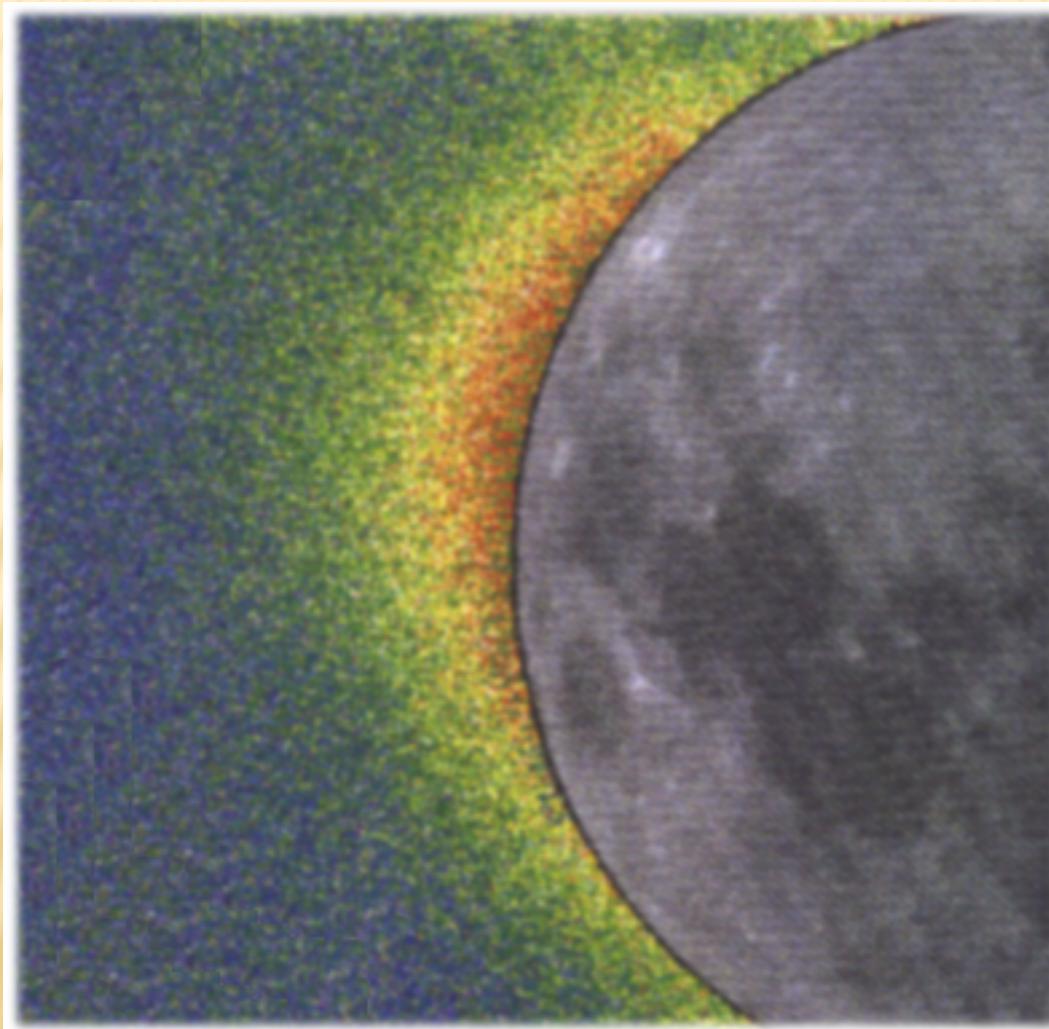
# OBSERVATIONS AND MODELS OF THE LUNAR SODIUM EXOSPHERE 1988 - 1999

Rosemary M. Killen, Dana M. Hurley, Menelaos Sarantos,  
Andrew E. Potter, Thomas H. Morgan, William M. Farrell,  
Shantanu Naidu & the DREAM Team

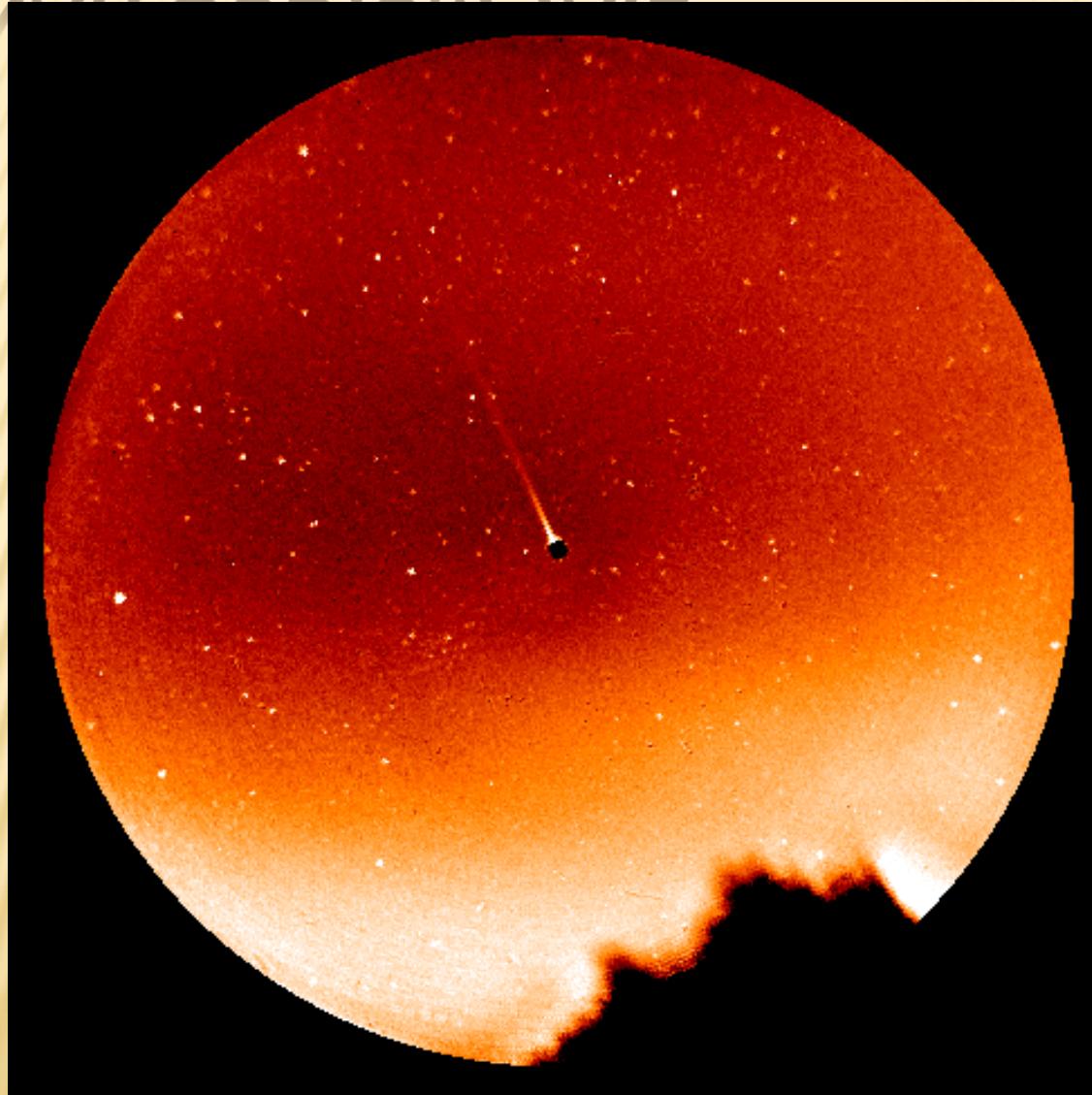


# LUNAR SODIUM EXOSPHERE

POTTER AND MORGAN, 1998



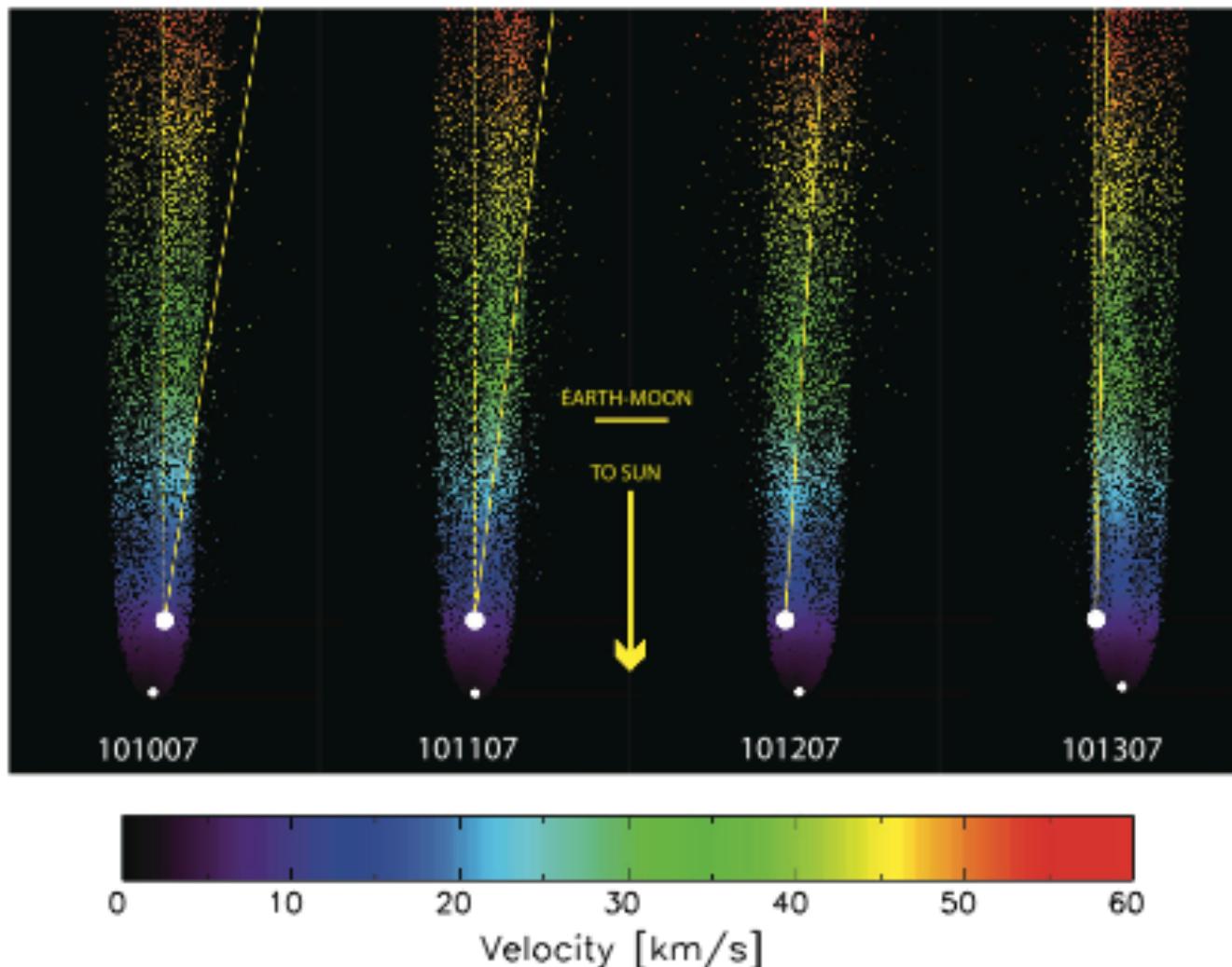
# LUNAR SODIUM TAIL



Mendillo et al.

# RADIATION PRESSURE ACCELERATION

M.R. Line et al./Icarus 219 (2012) 609–617



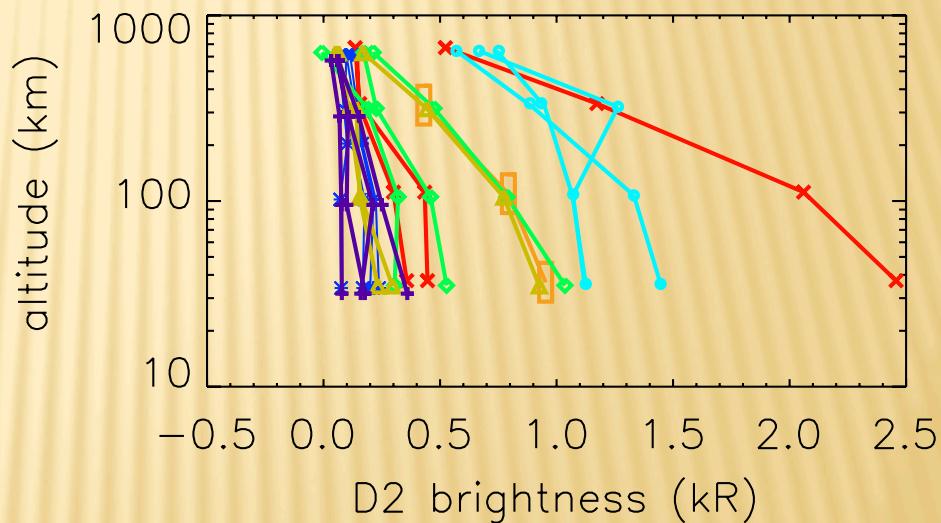
# OBSERVATIONS

---

- Mt. Lemon      April-May, 1998      Sprague
  - full moon to first quarter
  - N, S and illuminated limb
- McMath      Nov, 1998      Potter
  - full moon to last quarter
  - N, S, E, W limbs

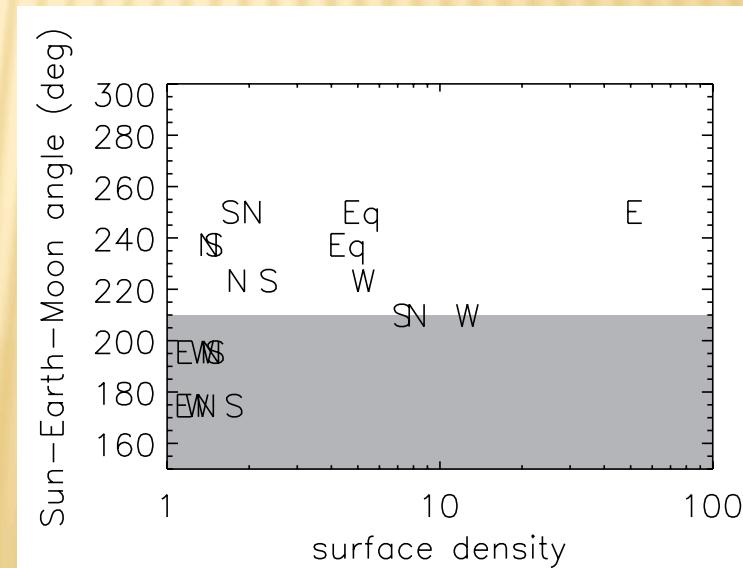
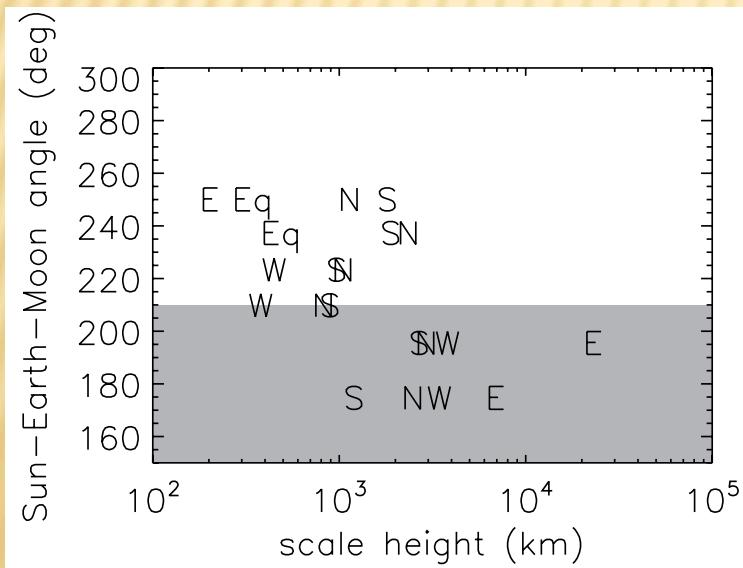
# SODIUM EXOSPHERE OBSERVATIONS

- ✖ Echelle spectrograph at McMath-Pierce solar telescope
  - + Sodium D1 and D2
  - + 1 week campaign during Nov. 1998
  - + Phase ranged from full moon to last quarter
  - + Each night acquired a set
    - ✖ From ~4 heights above surface, range 30-800 km
    - ✖ Each from N, S, E, and W of the Moon
  - + Calculated surface density and scale height from each position/night set of altitudes



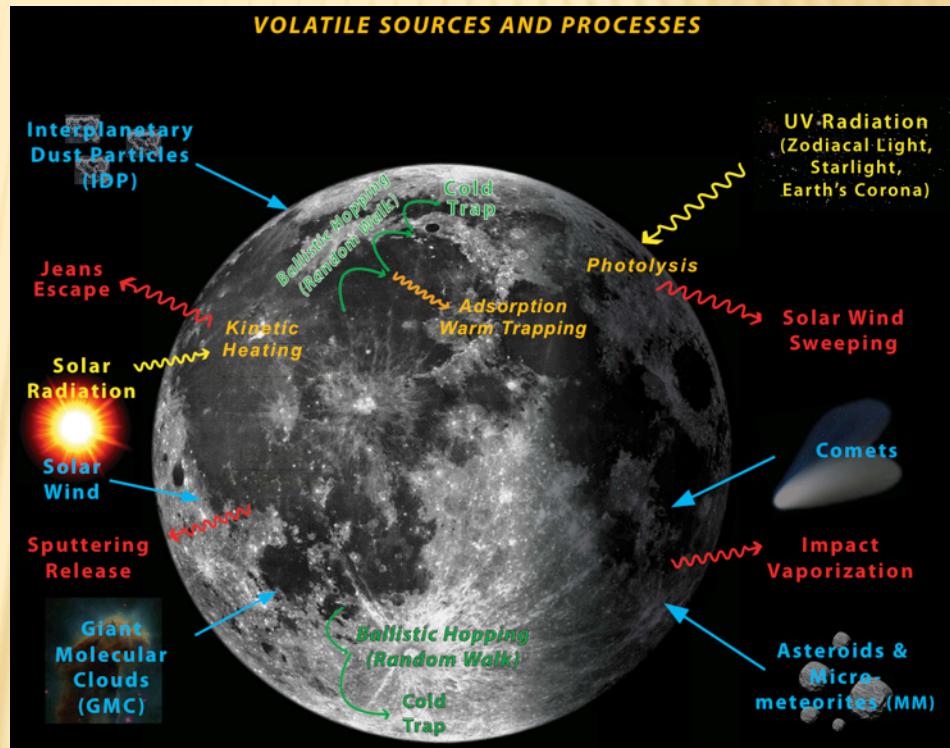
# OBSERVATIONS

- ✖ Within nominal magnetotail
  - + Surface density low (polar higher than equatorial)
  - + Scale height high (polar lower than equatorial)
- ✖ Outside of nominal magnetotail
  - + Surface density high (polar lower than equatorial)
  - + Scale height low (polar higher than equatorial)



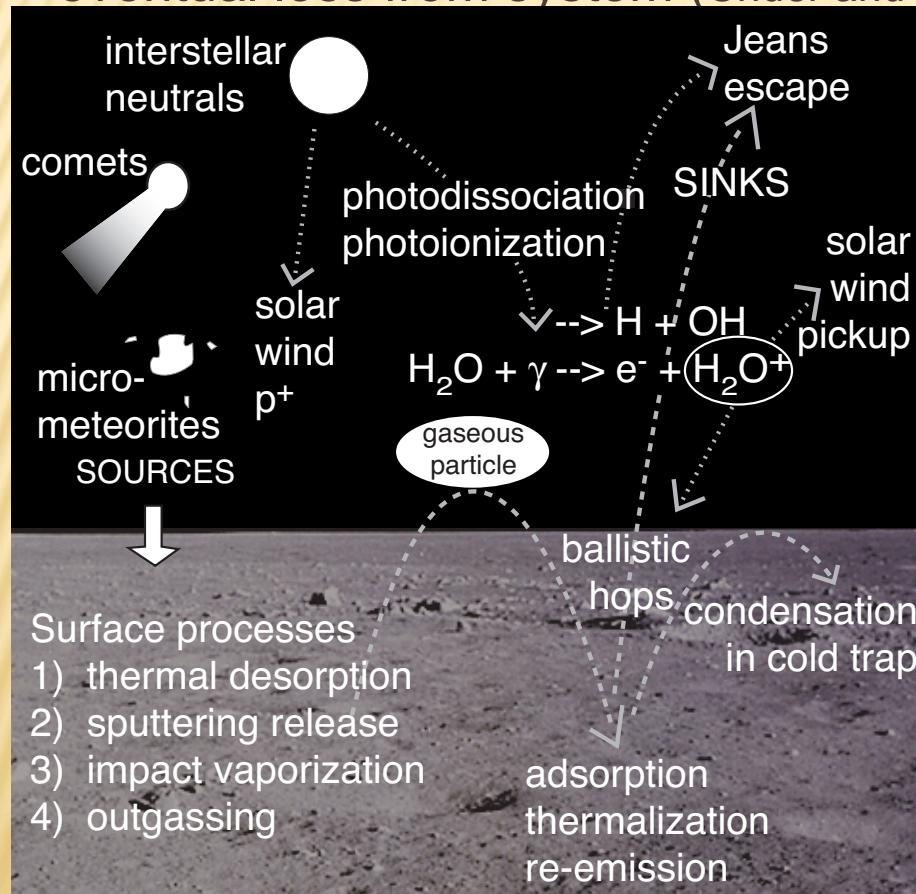
# LUNAR ATMOSPHERE

- ✖ Key factors in determining lunar atmospheric distribution
  - + Source distribution
  - + Surface temperature
  - + Surface encounters



# MONTE CARLO ATMOSPHERE MODEL

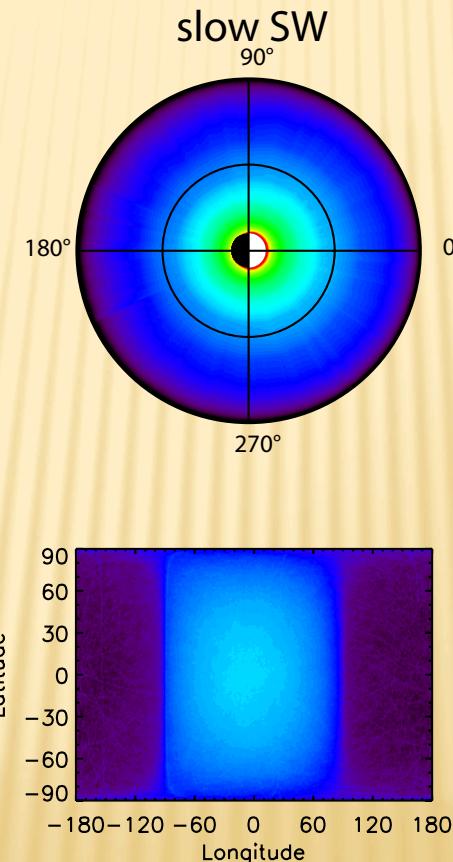
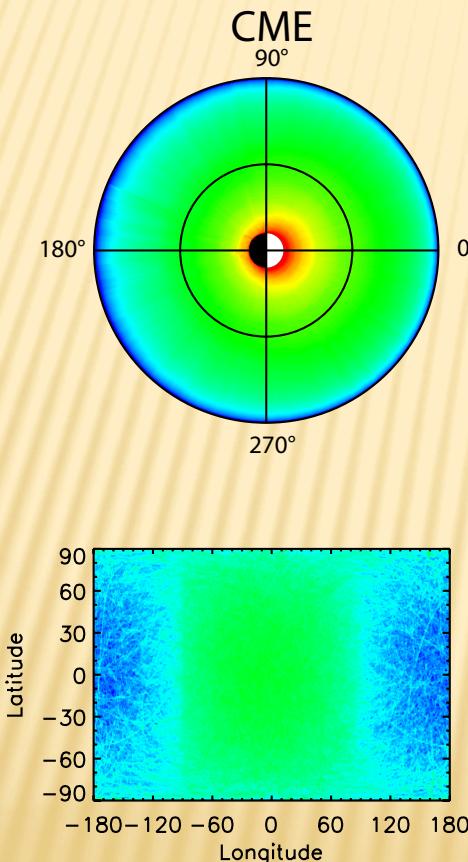
- Follows large number of particles from emission in atmosphere to eventual loss from system (Crider and Vondrak, 2000; 2002; Killen et al. 2012)



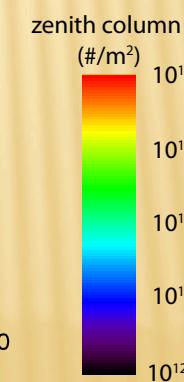
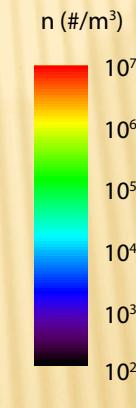
- Species (so far)
  - + H, H<sub>2</sub>, He, OH, H<sub>2</sub>O, Na, Ar, Ca, Mg, K, Hg, CO
- Source
  - + Position and velocity
- Trajectory calculation
  - + Gravity
  - + Radiation pressure
- Surface interaction
  - + Rerelease velocity
- Loss processes

# EXAMPLE OUTPUT

Sodium

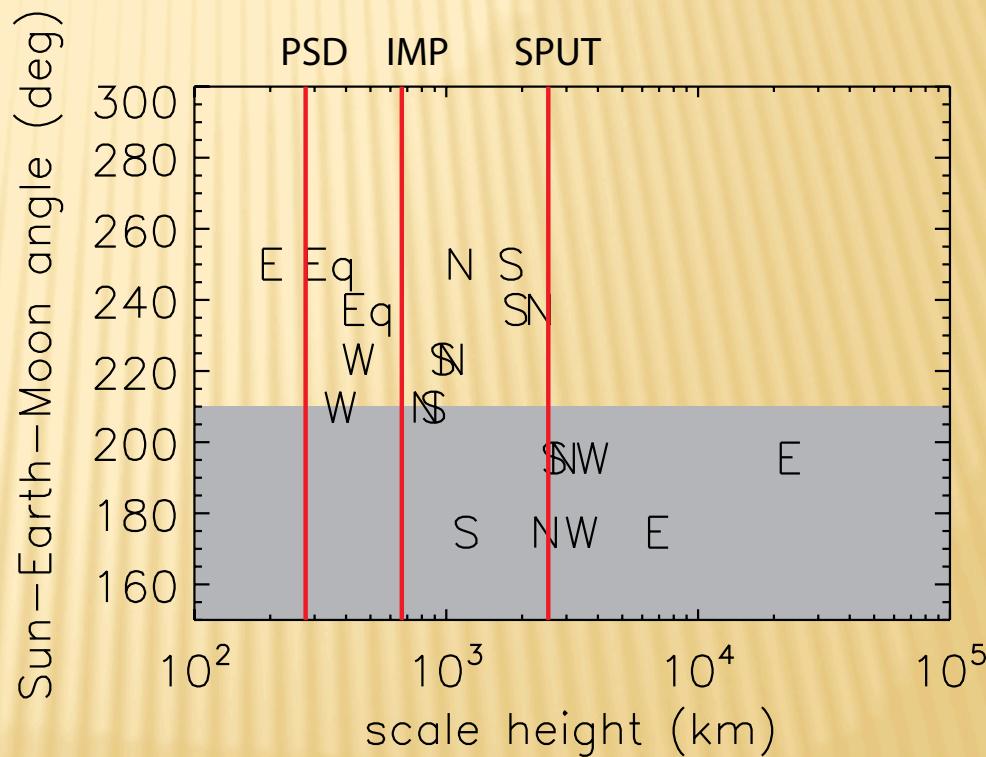


Killen et al., 2012



# SOURCES

- ✖ Photon stimulated desorption
  - + Dominant source
  - + 1200 K
  - + H~258 km
- ✖ Impact vaporization
  - + 3000 K
  - + H~645 km
- ✖ Sputtering
  - + Greatly reduced during magnetotail passage
  - + Highest energy—highest scale height
  - + H~2270 km



# SURFACE ENCOUNTERS

## + Physical processes

### + Adsorption

- ✖ Active sites
- ✖ Temporary cold traps
- ✖ Permanent cold traps

### + Re-release

- ✖ Bounce elastically
- ✖ Thermally accommodate
- ✖ Partial accommodation
- ✖ Inelastic bouncing

## ▪ Numerical handling

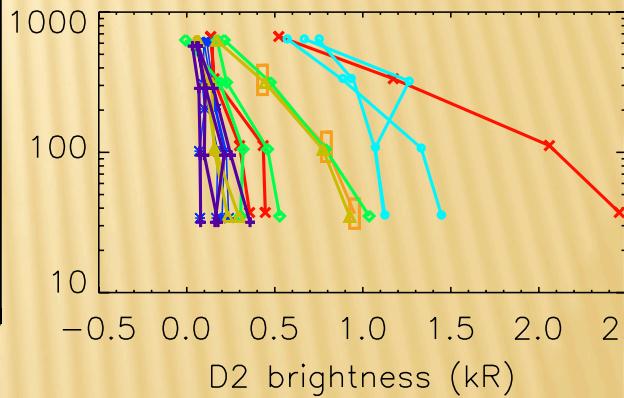
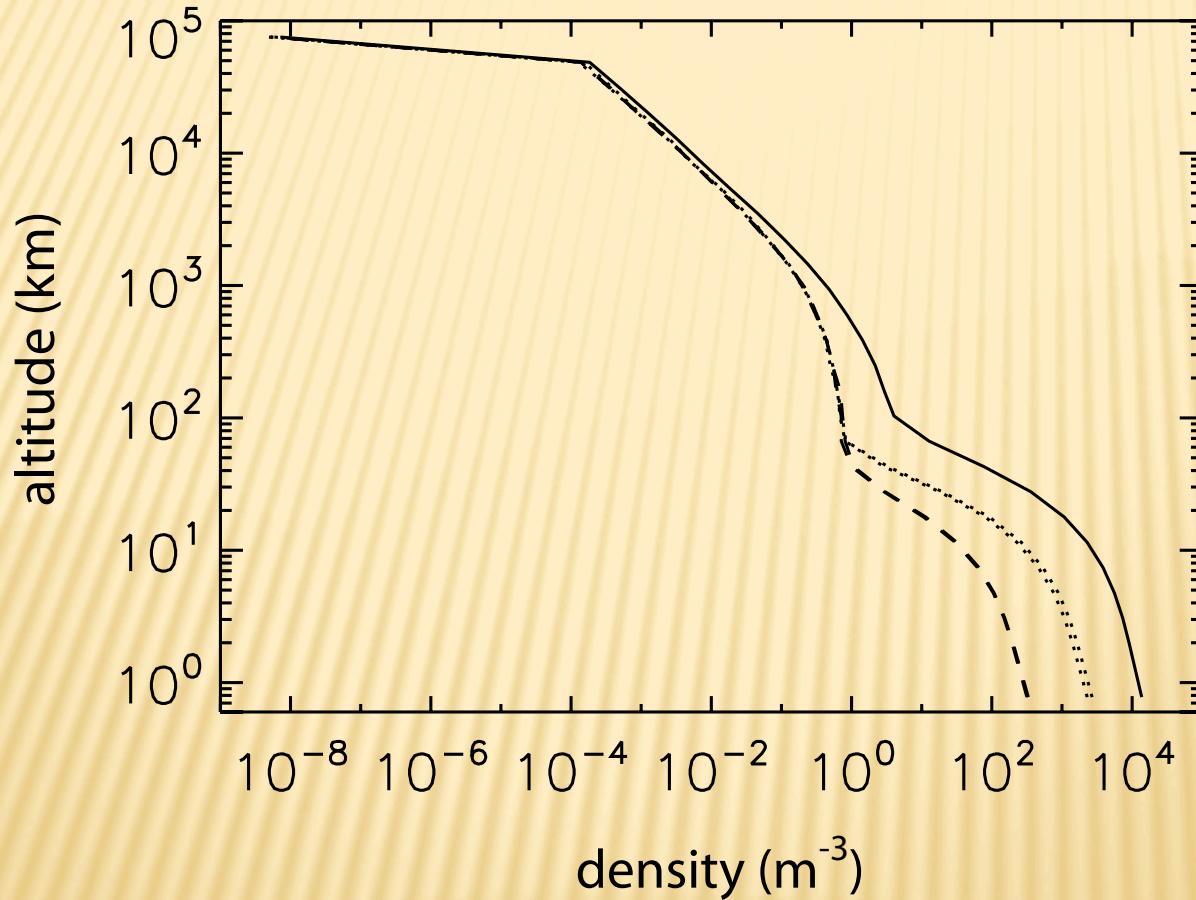
### ▪ Sticking

- Polar cold traps
- Nightside sticking
- How many make it back out when the surface warms back up?

### ▪ Release velocity

- Thermalization coefficient

# MODEL ALTITUDE PROFILES



# MODEL DENSITY BY POSITION

run parameters			density ratio		
Polar cold trap	reemited fraction	Thermalization	dawn/dusk	pole/dusk	subsolar/dusk
off	25	20	1.5	1.1	9.2
off	50	20	2.7	1.6	9.4
off	75	20	5.8	3.0	9.8
off	100	20	46.9	18.5	11.4
off	100	50	47.2	18.2	8.8
off	25	50	1.5	1.1	7.4
on	100	50	44.7	13.6	8.8
on	25	50	1.6	1.0	7.1
on	25	100	1.1	0.3	17.9
on	100	100	6.4	0.4	17.4

# MODEL DENSITY, REEMISSION FRACTION

Increasing reemission at dawn increases density at dawn

run parameters			density ratio		
Polar cold trap	reemited fraction	thermalization	dawn/dusk	pole/dusk	subsolar/dusk
off	25	20	1.5	1.1	9.2
off	50	20	2.7	1.6	9.4
off	75	20	5.8	3.0	9.8
off	100	20	46.9	18.5	11.4
off	100	50	47.2	18.2	8.8
off	25	50	1.5	1.1	7.4
on	100	50	44.7	13.6	8.8
on	25	50	1.6	1.0	7.1
on	25	100	1.1	0.3	17.9
on	100	100	6.4	0.4	17.4

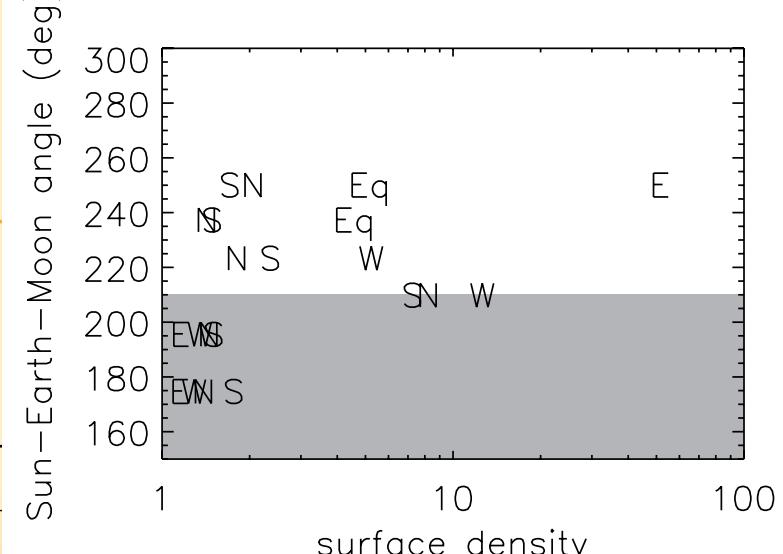
# MODEL DENSITY, POLAR COLD TRAPS

Cold trap sticking reduces density at poles

run parameters			density ratio		
Polar cold trap	reemited fraction	thermalization	dawn/dusk	pole/dusk	subsolar/dusk
off	25	20	1.5	1.1	9.2
off	50	20	2.7	1.6	9.4
off	75	20	5.8	3.0	9.8
off	100	20	46.9	18.5	11.4
off	100	50	47.2	18.2	8.8
off	25	50	1.5	1.1	7.4
on	100	50	44.7	13.6	8.8
on	25	50	1.6	1.0	7.1
on	25	100	1.1	0.3	17.9
on	100	100	6.4	0.4	17.4

# MODEL DENSITY

run parameters			dusk	pole/dusk	subsolar/dusk
cold trap	reemited fraction	thermalization			
off	25	20	1.5	1.1	9.2
off	50	20	2.7	1.6	9.4
off	75	20	5.8	3.0	9.8
off	100	20	46.9	18.5	11.4
off	100	50	47.2	18.2	8.8
off	25	50	1.5	1.1	7.4
on	100	50	44.7	13.6	8.8
on	25	50	1.6	1.0	7.1
on	25	100	1.1	0.3	17.9
on	100	100	6.4	0.4	17.4



# SODIUM EMISSION VS. LUNAR PHASE

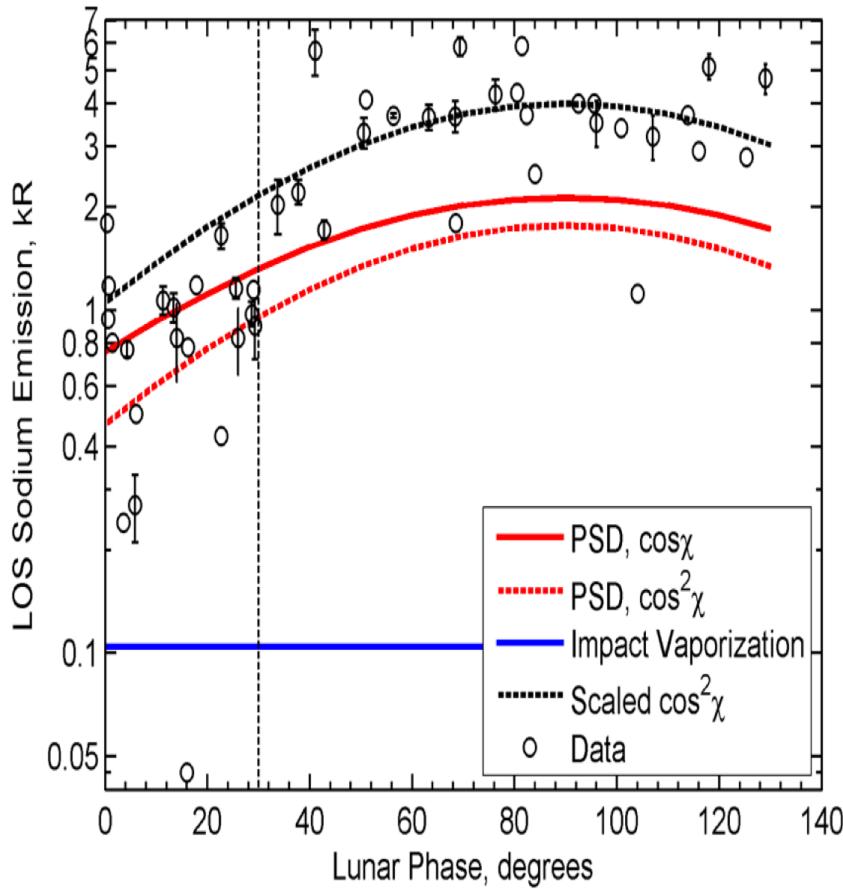


Figure 3. Lunar sodium emission data collected over many lunations (Sarantos et al., 2010) shows a decrease in emission when the moon is inside Earth's magnetosphere (left of dotted vertical line). The data could be explained either as ion-enhanced photon-stimulated desorption when the Moon is exposed to the solar wind, or as the effect of a colder, partly accommodated population seen when the line of sight goes through the subsolar point (quarter Moon). This effect is excluded here. Most data points used in this study probed tangent heights no shorter than 100 km.

Lunar sodium measured from Selene (Kaguya),  
Kagitani et al., 2009

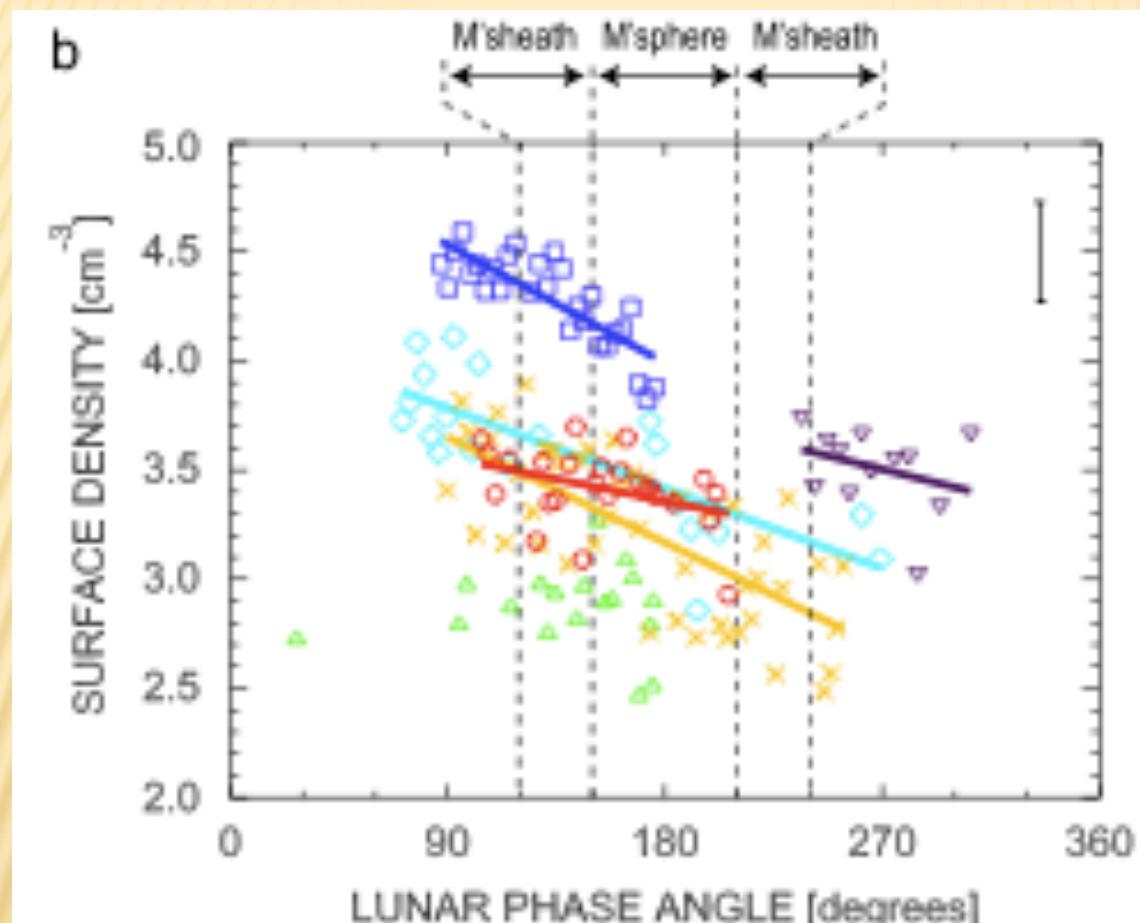


Fig. 2. Variation in surface density of sodium atoms vs. (a) day-of-year in 200

# CONCLUSIONS

- ✖ Sodium observations from Nov. 1998 showed a range of sodium density and scale height
  - + Varied with position on the Moon (pole vs. equator)
  - + Varied with phase of the Moon (magnetotail vs. solar wind)
- ✖ Observations indicate lower density over the poles than at equatorial terminator
  - + Model using permanent trapping at poles can reproduce pole/equator density variation
- ✖ Possible observation of dawn enhancement
  - + Model comparison to observations suggests moderate rerelease at dawn
- ✖ Observations indicate lower density in magnetotail
  - + Decrease in density in magnetotail is expected.
  - + Increase in scale height in magnetotail (importance of heavy ions in plasma sheet?)
  - + lower efficiency of PSD when Moon is shielded from the solar wind
  - + impact vaporization becomes dominant?

